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Maximum Power Point Tracking Algorithm for a Grid Connected PV-Fuel Cell-Wind Hybrid System

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***Abstract*— This paper presents a method to operate a grid connected hybrid system. The hybrid system composed of a Photovoltaic (PV) array, Proton exchange membrane fuel cell (PEMFC) and wind energy is considered. Two operation modes, the unit -power control (UPC) mode and the feeder-flow control (FFC) mode, can be applied to the hybrid system. In the UPC mode, variations of load demand are compensated by the main grid because the hybrid source output is regulated to reference power. Renewable energy is currently widely used. One of these resources is solar energy. The photovoltaic (PV) array normally uses a maximum power point tracking (MPPT) technique to continuously deliver the highest power to the load when there are variations in irradiation and temperature. Other renewable sources are PEMFC and Wind mill installed in the hybrid system. By changing the FC output power and Wind power the hybrid source output becomes controllable. Therefore, the reference value of the hybrid source output must be determined. In the FFC mode, the feeder flow is regulated to a constant, the extra load demand is picked up by the hybrid source, and, hence, the feeder reference power must be known. The system can maximize the generated power when load is heavy and minimizes the load shedding area. When load is light, the UPC mode is selected and, thus, the hybrid source works more stably. The changes in operating mode only occur when the load demand is at the boundary of mode change; otherwise, the operating mode is either UPC mode or FFC mode. Besides, the variation of hybrid source reference power is eliminated by means of hysteresis. This operating strategy will minimize the number of operating mode changes, improve performance of the system operation, and enhance system stability.**

***Keywords:* PV Array, Fuel cell, Wind Mill, UPC Mode, FFC Mode.**

I. INTRODUCTION

Hybrid power systems combine two or more energy conversion devices, or two or more fuels for the same device, that when integrated, overcome limitations inherent in either. Hybrid systems can address limitations in terms of fuel flexibility, efficiency, reliability, emissions and / or economics. Hybrid systems can be designed to maximize the use of renewable, resulting in a system with lower emissions than traditional fossil-fueled technologies. Hybrid systems can be designed to achieve desired attributes at the lowest acceptable cost, which is the key to market acceptance. Now a day‘s most popular renewable energy resources are solar, wind and fuel cells. The photovoltaic (PV) array normally uses a maximum power point tracking (MPPT) technique to continuously deliver the highest power to the load when there are variations in irradiation and temperature. The disadvantage of PV energy is that the PV output power depends on weather conditions and cell temperature, making it an uncontrollable source. Furthermore, it is not available during the night. In order to overcome these inherent drawbacks, alternative sources, such as PEMFC and wind mill, should be installed in the hybrid system. By changing the FC output power and wind mill output power, the hybrid source output becomes controllable.

The hybrid system can either be connected to the main grid or work autonomously with respect to the grid-connected mode or islanded mode, respectively. In the grid-connected mode, the hybrid source is connected to the main grid at the point of common coupling (PCC) to deliver power to the load. When load demand changes, the power supplied by the main grid and hybrid system must be properly changed. The power delivered from the main grid and PV array , wind mill as well as PEMFC must be coordinated to meet load demand. The hybrid source has two control modes: 1) unit-power control (UPC) mode 2) Feeder flow control (FFC) mode. In the UPC mode, variations of load demand are compensated by the main grid because the hybrid source output is regulated to reference power. Therefore, the reference value of the hybrid source output PMSref must be determined. In the FFC mode, the feeder flow is regulated to a constant, the extra load demand is picked up by the hybrid source, and, hence, the feeder reference power Pfeederref must be known.

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The proposed operating strategy is to coordinate the two control modes and determine the reference values of the UPC mode and FFC mode so that all constraints are satisfied. This operating strategy will minimize the number of operating mode changes, improve performance of the system operation, and enhance system stability.

II. PAGE LAYOUT

The system consists of a PV-FC-WIND hybrid source with the main grid connecting to loads at the PCC as shown in Fig. 1. The photovoltaic [3], [4], wind mill and the PEMFC [5],[6] are modeled as nonlinear voltage sources. These sources are connected to dc–dc converters which are coupled at the dc side of a dc/ac inverter. The dc/dc connected to the PV array works as an MPPT controller. Many MPPT algorithms have been proposed in the literature, such as incremental conductance (INC), constant voltage (CV), and perturbation and observation (P&O). The P&O method has been widely used because of its simple feedback structure and fewer measured parameters [7]. As PV voltage and current are determined, the power is calculated. At the maximum power point, the derivative (dP/dV) is equal to zero. The maximum power point can be achieved by changing the reference voltage by the amount of ΔV_{ref}.

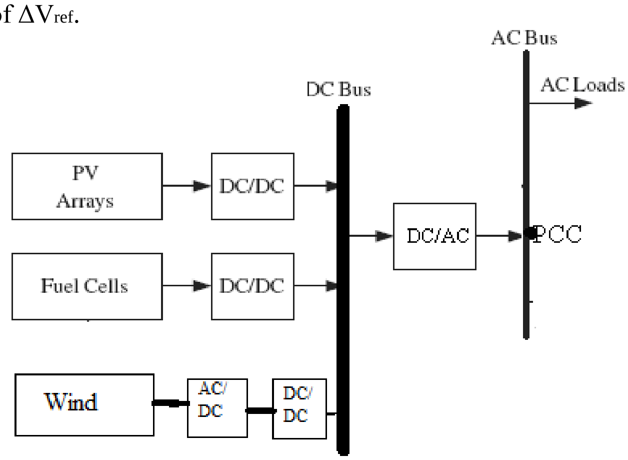

Fig. 1 Grid connected PV,FC Hybrid system

A. *PV Array Model*

PV modules still have relatively low conversion efficiency; therefore, controlling maximum power point tracking (MPPT) for the solar array is essential in a PV system. The amount of power generated by a PV depends on the operating voltage of the array. A PV‘s maximum power point (MPP) varies with solar insulation and temperature. It‘s V-I and V-P characteristic curves specify a unique operating point at which maximum possible power is delivered. At the MPP, the PV operates at its highest efficiency. Therefore, many methods have been developed to determine MPPT[3],[4].

$$I = I_{\mathrm{ph}} - I_{\mathrm{sat}} \left\{ \exp\left[\frac{q}{AKT}(V + IR_s) \right] - 1 \right\}. \qquad (1)$$

Where V and I represent the output voltage and current of the PV, respectively; R_s and R_{sh} are the series and shunt resistance of the cell; q is the electronic charge; I_{sc} is the light-generated current; Io is the reverse saturation current; n is a dimensionless factor; k is the Boltzmann constant, and T_k is the temperature in $_0$K. Equation (1) was used in computer simulations to obtain the output characteristics of a solar cell, as shown in Figure 3. This curve clearly shows that the output characteristics of a solar cell are non-linear and are crucially influenced by solar radiation, temperature and load condition. Each curve has a MPPT, at which the solar array operates most efficiently.

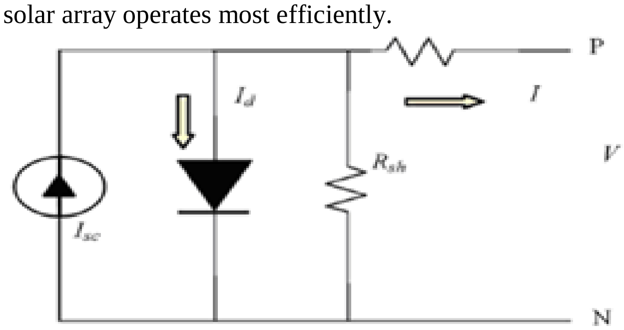

Fig. 2 Equivalent circuit of PV array

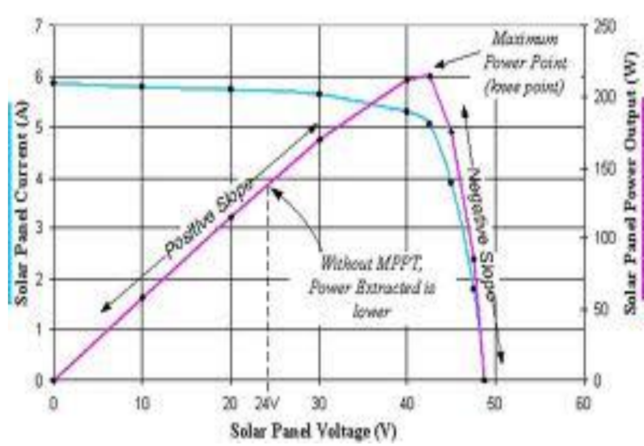

Fig. 3 V-I Characteristic of a solar cell

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B. PEMEC Model

Among various types of fuel cells, such as, Alkaline (AFC), Phosphoric Acid (PAFC), Molten Carbonate (MCFC), Solid Oxide (SOFC), Proton Exchange Membrane fuel cells (PEMFC) are the most promising. PEM fuel cells are favored for low temperature ~80^{0}C)-low pressure (~3atm) operation, high power density and good transient capability. A mathematical approach is presented for building a dynamic model for a PEM fuel-cell stack [5]. To simplify the analysis, the following assumptions are made

- One-dimensional treatment.
- Ideal and uniformly distributed gases.
- Constant pressures in the fuel-cell gas flow channels.
- The fuel is humidified H_2 and the oxidant is humidified air. Assume the effective anode water vapour pressure is 50% of the saturated vapour pressure while the effective cathode water pressure is 100%.
- The fuel cell works under 100^{0}C and the reaction product is in liquid phase.
- Thermodynamic properties are evaluated at the average stack temperature, temperature variations across the stack are neglected, and the overall specific heat capacity of the stack is assumed to be a constant.
- Parameters for individual cells can be lumped together to represent a fuel-cell stack. A schematic diagram of a PEM fuel cell and its internal voltage drops are shown in Fig. 4.

Under normal operating conditions, the fuel-cell output voltage is less than E_{Cell} . Activation loss, ohmic resistance voltage drop, and concentration over potential are voltage drops across the fuel cell, as shown in Fig. 4.

$$V_{out} = E_{Nerst} - V_{act} - V_{ohm} - V_{conc} \qquad (2)$$

Here 'E' is the eversible potential of each cell (in volts) To calculate the fuel-cell output voltage, the following estimations are used:

$$V_{Cell} = E_{Cell} - V_{act,cell} - V_{ohm,cell} - V_{conc,cell} \qquad (3)$$

Therefore the output voltage of the fuel-cell stack can be obtained as

$$V_{out} = N_{cell}V_{cell} = E - V_{act} - V_{ohm} - V_{conc} \qquad (4)$$

i. Activation Voltage Drop

Tafel equation, given below, is used to calculate the activation voltage drop in a fuel cell

$$V_{act} = \frac{RT}{\alpha zF}\ln\left(\frac{I}{I_0}\right) = T.[a + b\ln(I)] \qquad (5)$$

ii. Ohmic Voltage Drop

The ohmic resistance of a PEM fuel cell consists of the resistance of polymer membrane, the conducting resistance between the membrane and electrodes, and the resistances of electrodes. The overall ohmic voltage drop can be expressed as

$$V_{ohm} = V_{ohm,a} + V_{ohm,membrane} + V_{ohm,c} = IR_{ohm} \qquad (6)$$

iii. Concentration Voltage Drop

During the reaction process, concentration gradients can be formed due to mass diffusions from the flow channels to the reaction sites (catalyst surfaces). At high current densities, slow transportation of reactants (products) to (from) the reaction sites is the main reason for the concentration voltage drop. Any water film covering the catalyst surfaces at the anode and cathode can be another contributor to this voltage drop [1]. The concentration over potential in the fuel cell is defined as [18]

$$V_{conc} = -\frac{RT}{ZF}\ln\frac{C_S}{C_B} \qquad (7)$$

Where C_S is the surface concentration and C_B is the bulk concentration. According to Fick's First Law and Faraday's Law [19], the above equation can be rewritten as

$$V_{conc} = -\frac{RT}{ZF}\ln\left(1 - \frac{I}{I_{limit}}\right) \qquad (8)$$

The equivalent resistance for the concentration loss is

$$R_{conc} = \frac{V_{conc}}{I} = -\frac{RT}{zFI}\ln\left(1 - \frac{I}{I_{limit}}\right) \qquad (9)$$

C. Wind Turbine

Wind turbines are used to convert the wind power into electric power. Electric generator inside the turbine converts the mechanical power into the electric power. Wind turbine systems are available ranging from 50W to 2-3 MW. The energy production by wind turbines depends on

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the wind velocity acting on the turbine. Wind power is used to feed both energy production and consumption demand, and transmission lines in the rural areas.

Wind turbines can be classified with respect to the physical features (dimensions, axes, number of blade), generated power and so on. For example, wind turbines with respect to axis structure: horizontal rotor plane located turbines, turbines with vertical or horizontal spinning directions with respect to the wind. Turbines with blade numbers: 3-blade, 2-blade and 1- blade turbines.

On the other hand, power production capacity based classification has four subclasses [7].

- Small Power Systems
- Moderate Power Systems
- Big Power Systems
- Megawatt Turbines

D. MPPT Control

Many MPPT algorithms have been proposed in the literature [3][4], such as incremental conductance (INC), constant voltage (CV), and perturbation and observation (P&O)

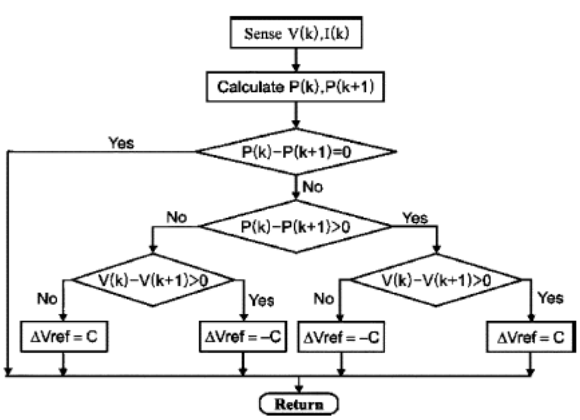

Fig. 4. P&O MPPT algorithm.

The two algorithms often used to achieve maximum power point tracking are the P&O and INC methods. The INC method offers good performance under rapidly changing atmospheric conditions. However, four sensors are required to perform the computations. If the sensors require more conversion time, then the MPPT process will take longer to track the maximum power point.

During tracking time, the PV output is less than its maximum power. This means that, longer the conversion time is, larger the power loss [7],[8]. On the contrary, if the execution speed of the P&O method increases, then the system loss will decrease. Moreover, this method only requires two sensors, which results in a reduction of hardware requirements and cost. Therefore, the P&O method is used to control the MPPT [9][10] process. The power-feedback control is used to achieve maximum power. As PV voltage and current are determined, the power is calculated. The maximum power point can be achieved by changing the reference voltage by the amount of ΔVref . In order to implement the MPPT algorithm, a buck-boost dc/dc converter is used as depicted in Fig. 5. The parameters L and C in the buck-boost converter must satisfy the following conditions [11]

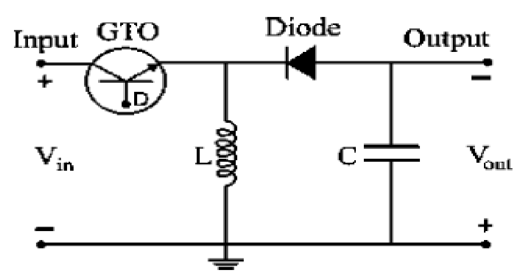

Fig. 5. Buck-boost topology.

The buck–boost converter is a type of DC-to-DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. It is a switched-mode power supply with a similar circuit topology to the boost converter and the buck converter. The output voltage is adjustable based on the duty cycle of the PWM generator. The basic principle of the buck–boost converter is fairly simple, The switch is turned-on, the input voltage source supplies current to the inductor, and the capacitor supplies current to the resistor (output load). When the switch is opened the inductor supplies current to the load via the diode. While in the on-state, the input voltage source is directly connected to the inductor (L). This results in accumulating energy in L. In this stage, the

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capacitor supplies energy to the output load. While in the off-state, the inductor is connected to the output load and capacitor, so energy is transferred from L to C and R.

III. Control and Operating Strategy of the Hybrid System

The control modes in the micro grid include UPC, FFC and mixed control mode[12]. In the UPC mode, the DGs (the hybrid source in this system) regulate the voltage magnitude at the connection point and the power that source is injecting. In this mode if a load increases anywhere in the micro grid, the extra power comes from the grid, since the hybrid source regulates to a constant power. In the FFC mode, the DGs regulate the voltage magnitude at the connection point and the power that is flowing in the feeder at connection point Pfeeder. With this control mode extra load demands are picked up by the DGs, which maintain a constant load from the utility view point. In the mixed control mode, the same DG could control either its output power or the feeder flow power. In other words, the mixed control mode is a coordination of the UPC mode and the FFC mode. Both of these concepts were considered in [13]–[16].The purpose of the operating algorithm is to determine the control mode of the hybrid source and the reference value for each control mode so that the PV is able to work at maximum output power. Fig6 shows the control algorithm diagram for determining the reference power automatically. Here C is constant. If ‘C’ increases the number of changes of PMSref will decrease and thus the performance of system operation will be improved. However, ‘C’ should be small enough so that the frequency does not change over its limits (±5%). In order to improve the performance of the algorithm, a hysteresis is included in the simulation model. The hysteresis is used to prevent oscillation of the setting value of the hybrid system reference power. At the boundary of change in PMSref, the reference value will be changed continuously due to the oscillations in PV maximum power tracking. To avoid the oscillations around the boundary, a hysteresis is included and its control scheme is to control PMSref is depicted in Fig 7.

$$P_{PV} + P_{FC} + P_{WIND} = P_{MSref} \quad (11)$$

A. Overall Operating Strategy for the Grid Connected Hybrid System

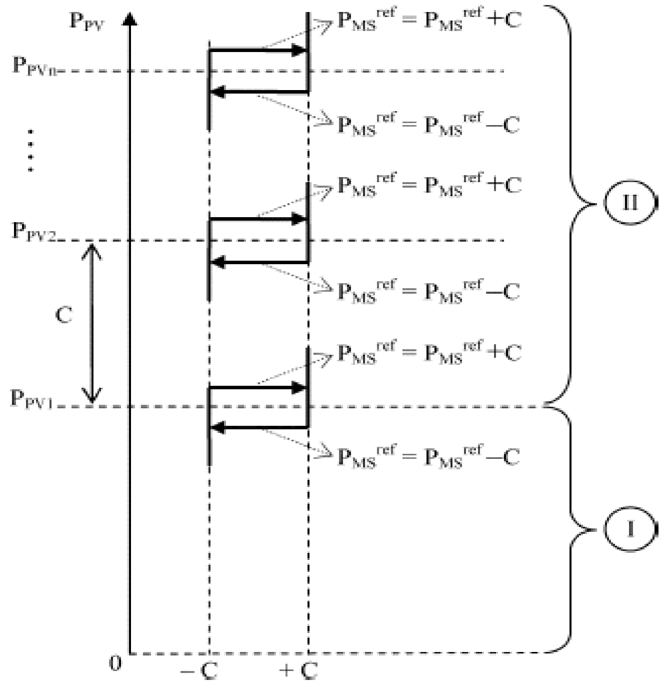

Fig. 6 Hysteresis control scheme for P_{MSref} control

This operating strategy must enable the PV to work at its maximum power point, FC output, and feeder flow to satisfy their constraints. Overall operating strategy is shown in Fig 6. Which involves two areas (Area I and Area II) and the control mode depends on the load power. If load is in Area I, the UPC mode is selected. Otherwise, the FFC mode is applied with respect to Area II. In the UPC area, the hybrid source output is PMSref. If the load is lower than PMSref , the redundant power will be transmitted to the main grid. Otherwise, the main grid will send power to the load side to match load demand. When load increases, the feeder flow will increase correspondingly. If feeder flow increases to its maximum Pfeedermax , then the feeder flow cannot meet load demand if the load keeps increasing. In order to compensate for the load demand, the control mode must be changed to FFC with respect to Area II. Thus, the boundary between Area I and Area II Pload1 is

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IV. SIMULINK CIRCUIT AND SIMULATION RESULTS

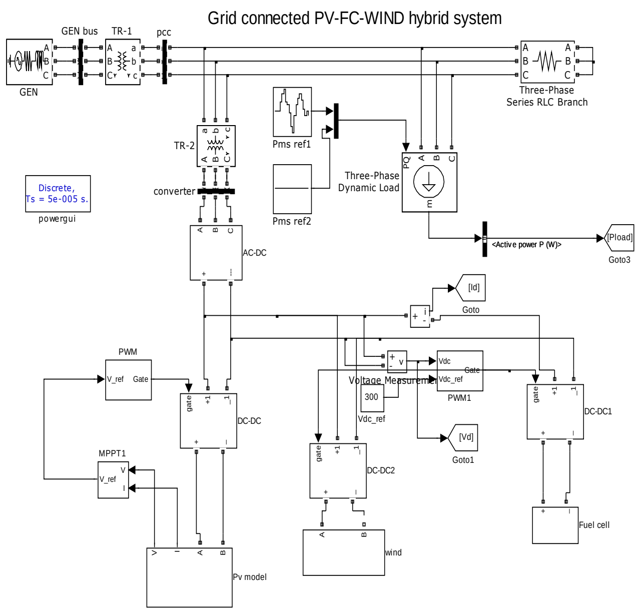

Fig 7 Simulation Circuit of the proposed circuit

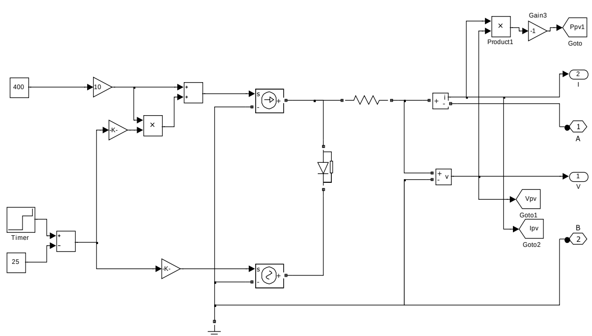

Fig 8 Simulation model for PV array

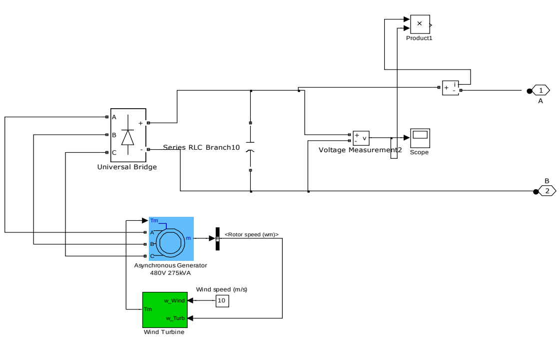

Fig 9 Simulation model for wind mill

A. *Simulation Results without Hysteresis Control*

A simulation was carried out by using the system model shown in Fig. 7

In order to verify the operating strategy, the load demand and PV output were time varied in terms of step. According to the load demand and the change of PV output, PFC, $P_{feeder}{}^{ref}$, $P_{MS}{}^{ref}$ and the operating mode were determined by the proposed P&O MPPT algorithm. Figs 10a,10b shows the simulation results of the system operating strategy. The changes of PPV and PLoad are shown in Fig. 10a and Fig. 10b.

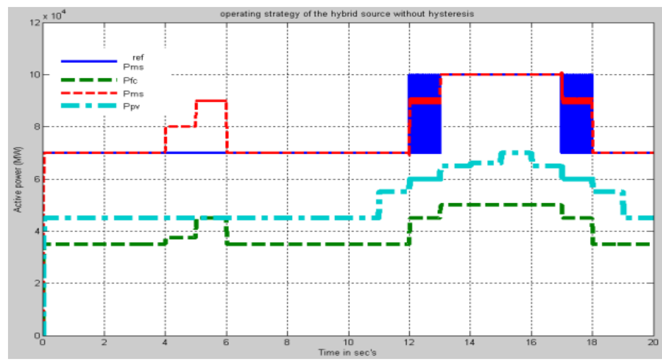

Fig. 10a Simulation result of operating strategy of the hybrid source without hysteresis

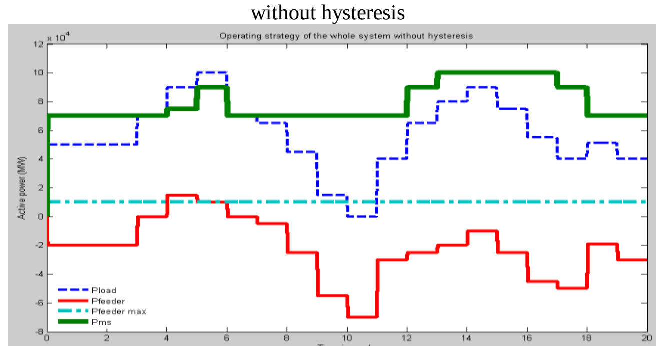

Fig. 10b Simulation result of operating strategy of the whole system without hysteresis

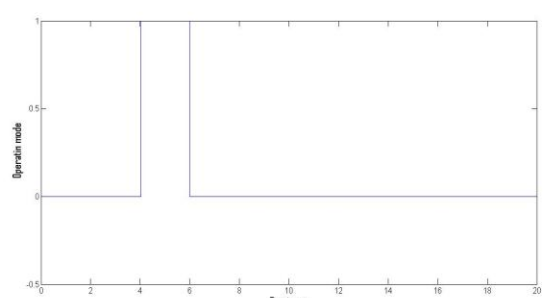

Fig. 10c Simulation result of change of operating modes

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B. Improving Operation Performance by Using Hysteresis

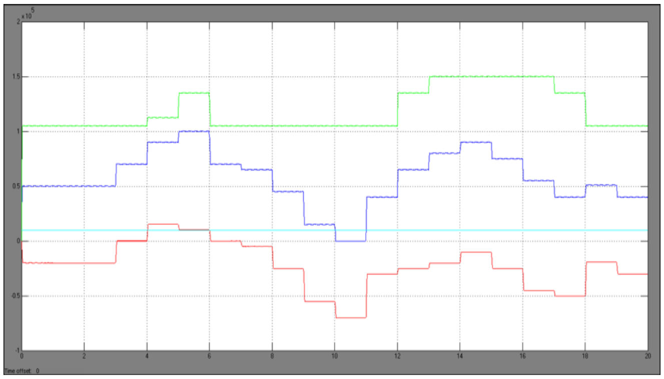

Fig 11 Simulation result of operating strategy of whole system with hysteresis control

V. CONCLUSIONS

The main operating strategy, shown in Fig. 8, is to specify the control mode; the Flow chart shown in Fig. 6 is to determine PMSref in the UPC mode. With the operating algorithm, PV always operates at maximum output power, PEMFC operates within the high-efficiency range (PFClow/PFCup), and feeder power flow is always less than its maximum value (PFeedermax) . The change of the operating mode depends on the current load demand, the PV output, wind output and the constraints of PEMFC and feeder power. The system can maximize the generated power when load is heavy and minimizes the load shedding area. When load is light, the UPC mode is selected and thus, the hybrid source works more stably. The changes in operating mode only occur when the load demand is at the boundary of mode change; otherwise, the operating mode is either UPC mode or FFC mode. Besides, the variation of hybrid source reference power PMSref is eliminated by means of hysteresis. In addition, the number of mode changes is reduced. As a consequence, the system works more stably due to the minimization of mode changes and reference value variation. In brief, the proposed operating algorithm is a simplified and flexible method to operate a hybrid source in a grid-connected microgrid. It can improve the performance of the system‘s operation; the system works more stably while maximizing the PV output power.

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